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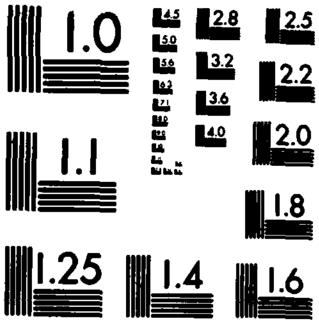

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We briefly summarize the existing knowledge on XUV operation of Free-Electron Lasers. The standard classical analysis is valid until about 1Å wavelength if a high energy electron beam is used. If a low energy beam is used, the limiting wavelength is larger. Other topics discussed are electron shot noise, photon statistics, photon and electron quantum effects, coherence, high-gain collective effects, higher harmonics, and transverse optical effects.

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SUMMARY DISCUSSION: THEORETICAL ASPECTS OF XUV FREE ELECTRON LASERS

W.B. Colson

Quantum Institute, University of California, Santa Barbara, CA 93106

Panel Members: W. Becker, S. Benson, A. Bhowmik, R. Cover, J. Gea-Banacloche, J. Goldstein, Y. Hsu, J. McIver, G. Moore, J. Murphy, A. Renieri, C. Tang.

INTRODUCTION

From the talks presented at this meeting, it appears quite possible that free electron lasers (FELs) can produce 500-100 Å radiation. The task of this panel is to evaluate the existing theoretical FEL work in this new wavelength region and to try to find new problems which have not been evaluated. The topics of our discussion include electron shot noise, photon statistics, photon and electron quantum effects, coherence, high-gain collective effects, higher harmonics, and transverse optical modes. We briefly summarize the existing knowledge on these topics for FELs, and assess the importance of the topic to the XUV FEL operation.

To begin, it is useful to consider some basic physics relevant to XUV operation. Counting electrons or photons involves knowing a relevant volume element. As a first estimate of the volume element, consider the "transverse optical mode area" times "N longitudinal wavelengths of light," where N is the number undulator periods. The number of photons in this volume determines the fluctuations present within the FEL gain bandwidth,[1] which is N^{-1} times the fundamental optical frequency $\omega = kc = 2\pi c/\lambda$. During the interaction, N optical wavelengths pass over an electron as it passes through N undulator periods. Therefore the length $N\lambda$ determines the sampling uncertainty of the optical field as measured by an electron in the FEL beam. The transverse resonator mode area is roughly λz_o where z_o is the resonator Rayleigh length; the length z_o is the distance over which the light beam cross-section doubles it's area. In a typical FEL design, z_o is usually made comparable to the undulator length $L=N\lambda_o$. Then, the volume element is $V \approx N\lambda^2 z_o \approx N\lambda^2 L \approx N^2\lambda^2\lambda_o$.

Another way to estimate this volume is from the size of the "coherent" radiation cone. Incoherent spontaneous radiation is emitted into a characteristic forward angle γ^{-1} when the electron energy is γmc^2. The angular range for coherent emission[1] is $\gamma^{-1}N^{-\frac{1}{2}}$ which is typically much smaller than γ^{-1} since $N >> 1$. In the longitudinal direction we still consider N optical wavelengths so that the volume defined by coherent emission over an interaction length L is $V \approx N\lambda L^2/\gamma^2 N \approx N^2\lambda_o^2\lambda/\gamma^2$. The wavelength of an FEL is related to the undulator wavelength λ_o through $\lambda \approx \lambda_o/2\gamma^2$. We find agreement with our first calculation, and again the relevant volume element is $V \approx N^2\lambda^2\lambda_o$.

The fact that $V \propto \lambda^2$ at the root of the following questions about quantum statistics in short wavelength applications. The number of photons and electrons contributing to coherent emission becomes quite small when the optical wavelength is decreased. As an example, use $\lambda = 500$ Å, $z_o \approx L \approx 15$ m, and $N = 500$ periods to find that $V \approx 10^{-5}\ \mathrm{cm}^3$.

ELECTRON SHOT NOISE

Electron shot noise is a classical concept caused by the discrete, random position of electrons in the beam. The average number of electrons found in the volume V is $\bar{n}_e \approx \rho_e V$. Typically, a good FEL will have $\rho_e \approx 10^{12}$ electrons/cm^3 so that $\bar{n}_e \approx 10^7$ electrons. The random shot noise fluctuations, $\bar{n}_e^{1/2} << \bar{n}_e$, are small for such a large number of electrons.[1] Therefore, shot noise does not appear to seriously influence coherence in XUV FELs at $\lambda \approx 500$ Å.

At shorter wavelengths, like $\lambda \approx 1$ Å, the shot noise can be more important because the volume element for counting decreases. Several papers have evaluated the effects of shot noise.[2-7] Generally start-up from noise was observed to be faster with significant shot noise, and FEL coherence did not deteriorate at saturation.

PHOTON NOISE

The electron emission probability per pass through the undulator can be written in a simple form[8] $w_T \approx \pi N\alpha[K/(1+K^2)]^2$ where $\alpha = 1/137$, $K = eB\lambda_o/2\pi mc^2$, and B is the undulator field strength. A smaller number of photons are actually saved in the resonator mode;[1] this rate is estimated as $w_s \approx 0.1\alpha LK^2/(1+K^2)z_o$. Typically $K \geq 1$, and $L/z_o \approx 1$ so that $w_T \approx 5$ photons-emitted/electron-pass, and only $w_s \approx 10^{-3}$ photons-saved/electron-pass.

The number of photons saved each pass in the volume element V is then $\bar{n}_s \approx \rho_e V w_s \approx 10^4$ photons. We see that during FEL start-up $\bar{n}_s >> 1$ even after just one pass. Since the spontaneous emission events are independent, photon statistics are Poissonian if the gain is low. The small fluctuations from $\bar{n}_s^{1/2}$ should not be expected to significantly reduce classical gain estimates. In steady-state saturation, the photon number is even higher with presumably lower fluctuations. Photon statistics, like shot noise, do not appear to be a problem for XUV FELs at $\lambda \approx 500$ Å.

At low electron densities exotic processes like "photon anti-bunching" have a possibility of being observed in an XUV FEL if careful studies are made.[9] This requires that the FEL be used as an amplifier and that the external laser wavelength be chosen for negative gain. The statistical result predicted is that the emission of one photon makes it less likely that another photon will follow.

In our discussion there was general agreement that statistical properties of light will be difficult to observe in XUV FELs and a classical representation of the optical field is adequate in most applications.[10-16] Specific results and approaches were not accepted by all panel members, however.

ELECTRON WAVE FUNCTIONS

Another type of quantum effect occurs when the electron wave packet is comparable to the optical wavelength λ during the interaction. Requiring that the electron momentum stay within the FEL gain bandwidth N^{-1} after interacing with a photon gives the limit[17] $\lambda_c N < \lambda\gamma$ where $\lambda_c = \hbar/mc$ is the Compton wavelength. This condition is well satisfied for storage rings with high γ, but not satisfied for low "two-stage" FEL mechanisms.[2,5,18] If this quantum limit is violated, then a fully quantum mechanical treatment finds that the gain is significantly reduced.[19] Electron quantum effects in FELs are new interesting physics problems.[20]

COHERENCE EVOLUTION

In a storage ring, the Renieri saturation limit[21] determines that there are about 10^5-10^7 photons in our relevant volume element. The large number of photons in V from start-up through saturation means that photon statistics may be measured in an XUV FEL, but they will not produce fluctuations which will destroy the gain mechanism. The evolution from spontaneous emission to a coherent state has been explored by many researchers in several different ways.[2,4,7,14-16] A quantum mechanical approach with classical electrons can be shown to always produce coherent Glauber states.[22] P. Sprangle, C.M. Tang and I. Bernstein[4] have shown that coherence evolves fast compared to the saturation process. Generally the ideas on coherence evolution seem to be in good shape, but a nice comprehensive theory might still be needed.

HIGH-GAIN EFFECTS

It is interesting to note that the major problem of short wavelength FELs has traditionally been regarded as low gain. But now, some FEL designs presented at this meeting lead to high gain. The design goals were ambitious, because high mirror losses are anticipated. When gain >> 1, both the amplitude and phase of the optical field change significantly so that the gain mechanism becomes "collective." There has already been a great deal of work on this topic applied to FELs and, extends back to some of the first analyses used to understand the physics of FELs.[23-30] The high gain effects are generally based on a single-mode analysis using plasma dispersion relations, but have also been explored using self-consistent single particle theory.[28-30] New theoretical work is needed to develop a multimode analysis of high-gain effects.

HARMONICS

The coupling to high frequency harmonics is an important method of extending FELs to shorter wavelength. Several papers have now calculated the new coupling in higher harmonics.[30-33] The extra factor in the gain is $n[J_{(n-1)/2}(n\xi)-J_{(n+1)/2}(n\xi)]^2$ where $\xi = K^2/4(1+K^2/2)$ and $n = 1,3,5,7...$ labels the harmonic number. These Bessel functions reduce the gain when n is large and undulators with small $K \ll 1$ cannot reach higher harmonics. The trick of using higher harmonics is not "exotic" since three experiments (Los Alamos National Lab, TRW at Stanford, and Frascati, Italy) have already observed coherent emission in higher harmonics.

The coupling to higher harmonics may be used in an FEL oscillator configuration making use of selective mirrors to encourage growth at a particular wavelength.[32] It is also possible to use higher harmonics in a single pass system. The klystron configuration uses a "buncher" section with an external laser to create a modulated electron beam.[34-36] Coherent emission from that beam is then extracted in a radiator section. Generally speaking, these kinds of tricks can produce about one tenth the wavelength of a conventional FEL.

TRANSVERSE OPTICAL MODES

At short wavelengths the volume element V decreases while the photon energy $\hbar kc$ increases. Therefore the XUV FEL tends to work at high power densities with a mode area roughly given by $z_0\lambda$. This area is about 1 mm in diameter, and is about the size of the electron beam cross-section in a storage-ring. A storage-ring with an elliptically shaped electron beam which is roughly the same size as the XUV optical mode gives a new transverse mode problem to solve. New resonator modes may be specifically designed to better "fit" the electron beam.[37] In combination with high gain, severe distortion of the transverse optical mode may be possible. Generally this topic can be solved with numerous theoretical techniques now available,[38-42] but they need to be applied to the specific XUV case.

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